# Tune Modulation from Beam-Beam Interaction and Unequal Radio Frequencies in RHIC

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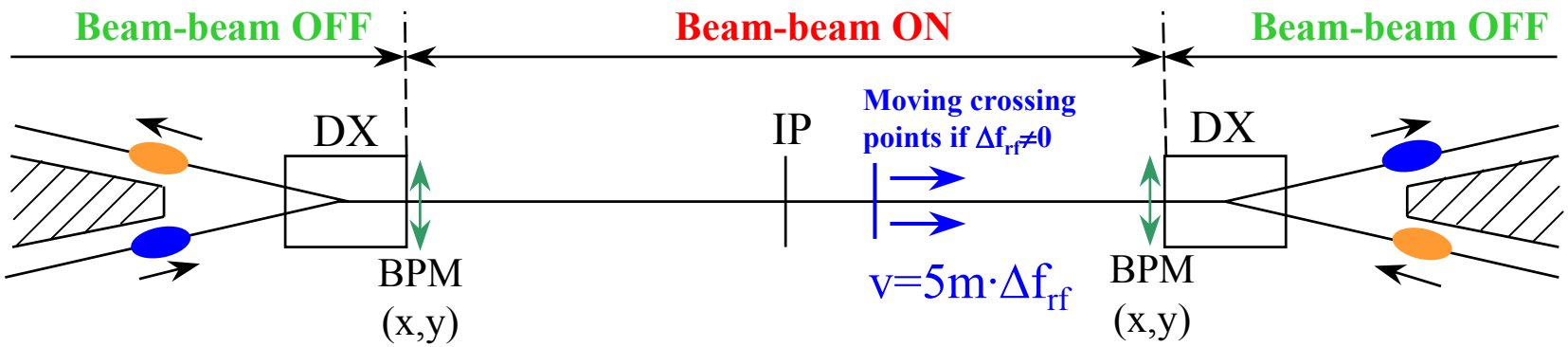
1. RHIC interaction regions and rf systems
2. Moving interaction points
3. Examples of observations
4. Frequency and waveforms of tune modulation
5. Summary

- Blue and Yellow rings independent (except DX):
  - Independent control of transition jump
  - Need to accommodate different species
  - Synchronization and cogging at store
    (frequent recogging considered for polarized proton run, every 5 min)
- Rf frequencies were not synchronized initially
  - 28 MHz acceleration system, $h = 360$
  - 197 MHz storage system, $h = 2520$ (= 7×360)



$$\Delta T = T_1 - T_2 = \frac{h}{f_{rf,1}} - \frac{h}{f_{rf,2}} = \frac{h \Delta f_{rf}}{f_{rf}^2}$$

$$v_{CP} = \frac{c}{2} \frac{\Delta f_{rf}}{f_{rf}}$$

Longitudinal velocity of crossing point

| | |
|---|---|
| $T$ | revolution time |
| $h$ | harmonic number |
| $c$ | beam velocity (≈ speed of light) |
| $f_{rf}$ | radio frequency |
| $\Delta f_{rf}$ | difference between two rings |

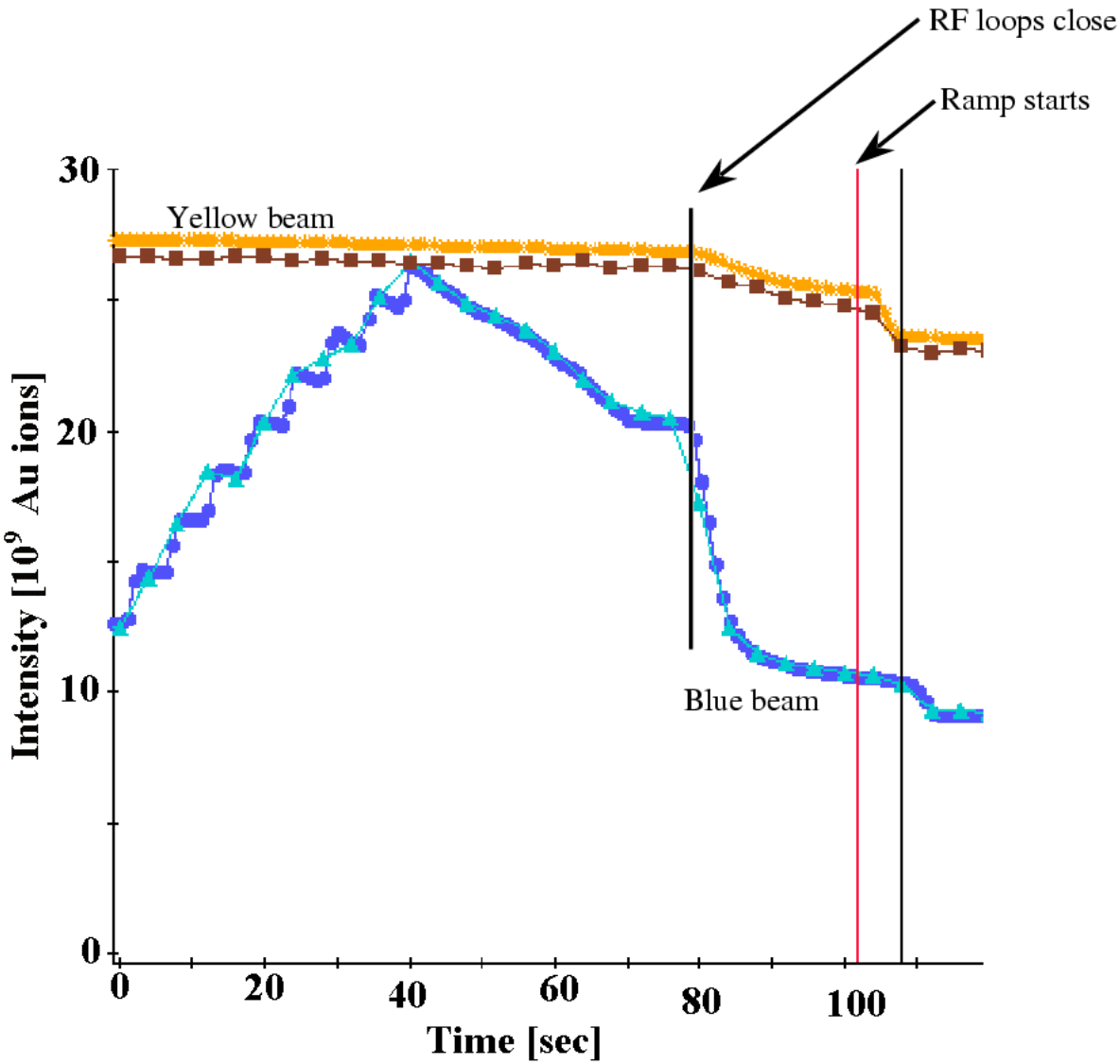
Example 1: RHIC Au-Au

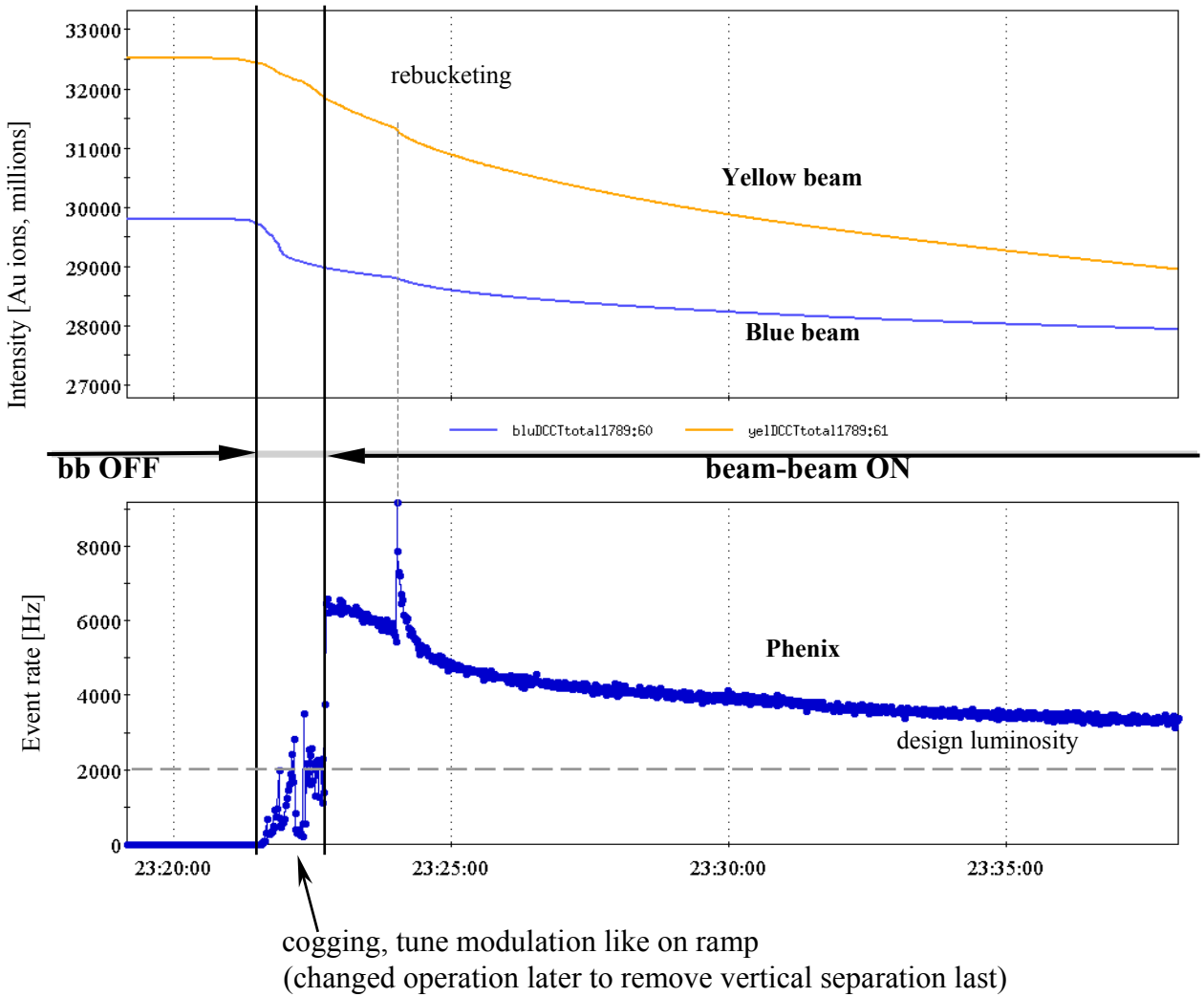
$f_{rf}$ = 28 MHz, $\Delta f_{rf}$ = 5 Hz → $v_{CP}$ = 27 ms$^{-1}$ → **modulated interaction**

Example 2: RHIC d-Au, same rigidity at injection

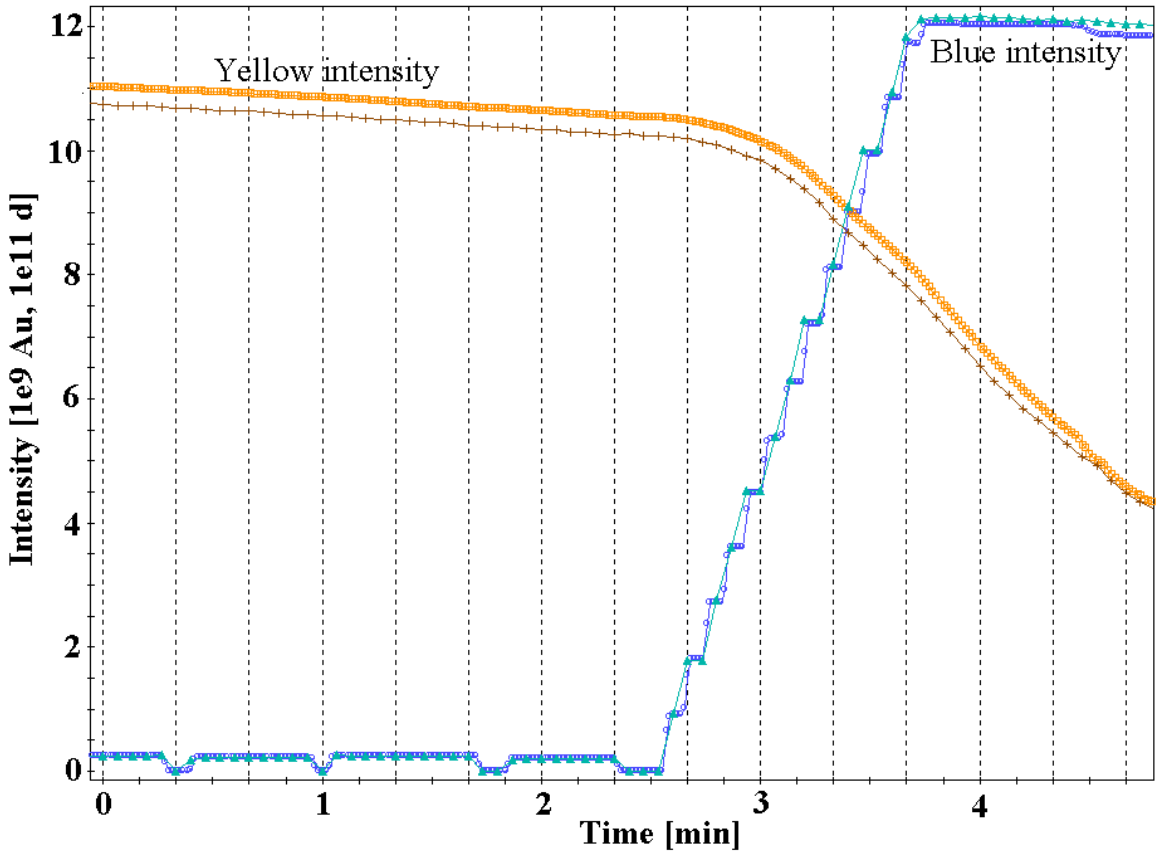
$f_{rf}$ = 28 MHz, $\Delta f_{rf}$ = 44 kHz → $v_{CP}$ = 3 m/turn → **pseudo-random interaction**

# Tune modulation from unequal rf frequencies – injection






**Addition of beam-beam interaction leads to significant reduction in beam lifetime**

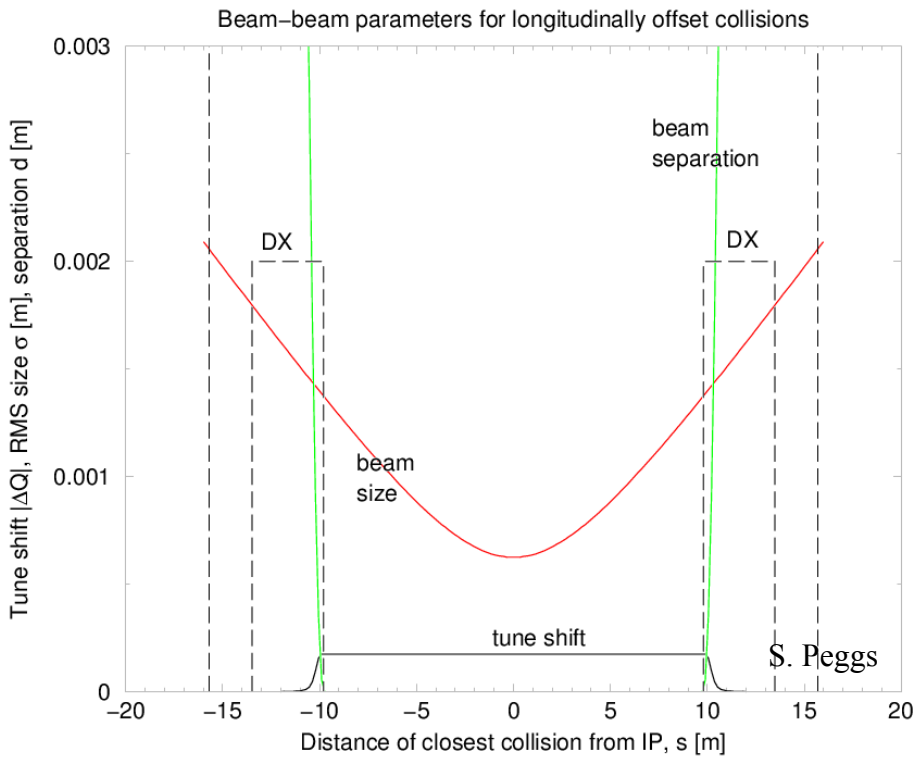



Beam-beam effect during injection, d and Au with same rigidity ($\rightarrow$ different $\gamma$)
$\Delta f_{rf}$ = 44kHz, vertical separation=10mm

$\rightarrow$ Pseudo-random dipole kicks lead to emittance increase

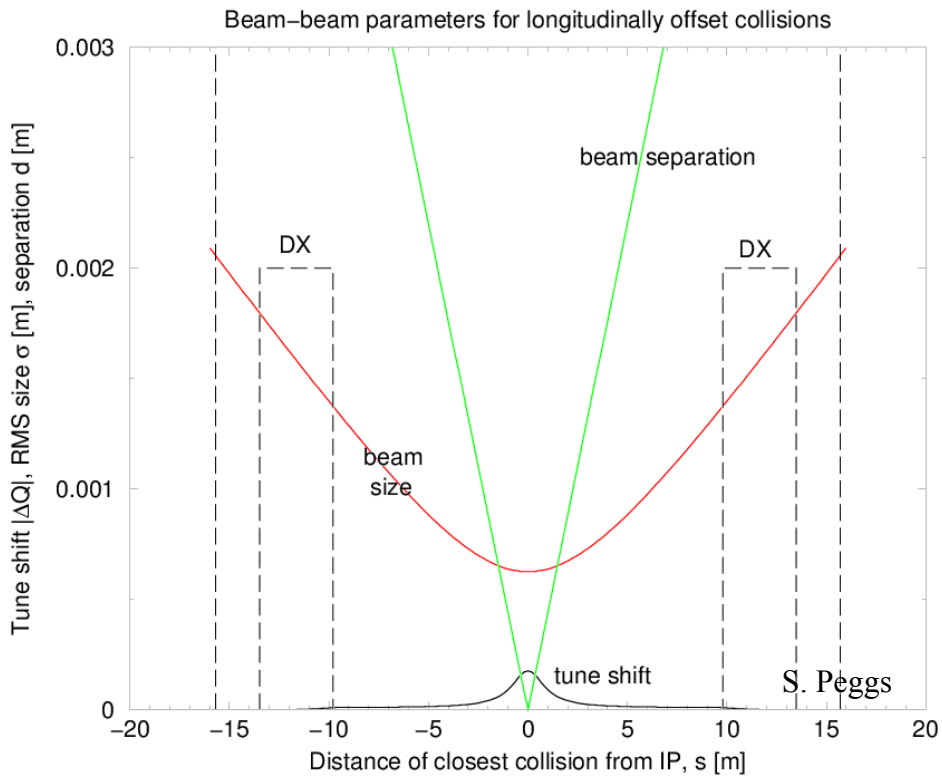
# Tune modulation wave form is determined by crossing angle and $\Delta f_{rf}$

## No crossing angle

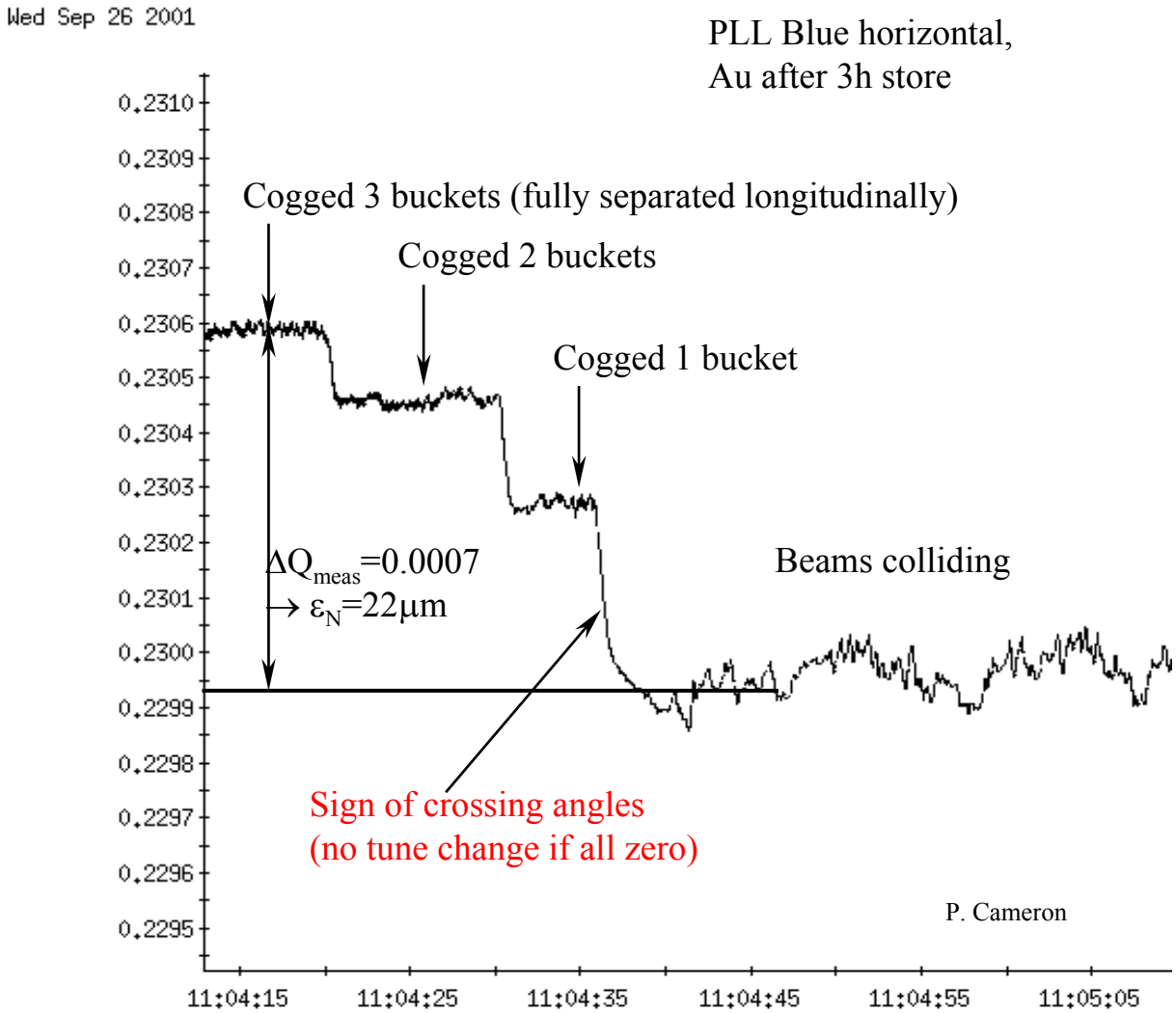



Tune constant between DX, sharp edges

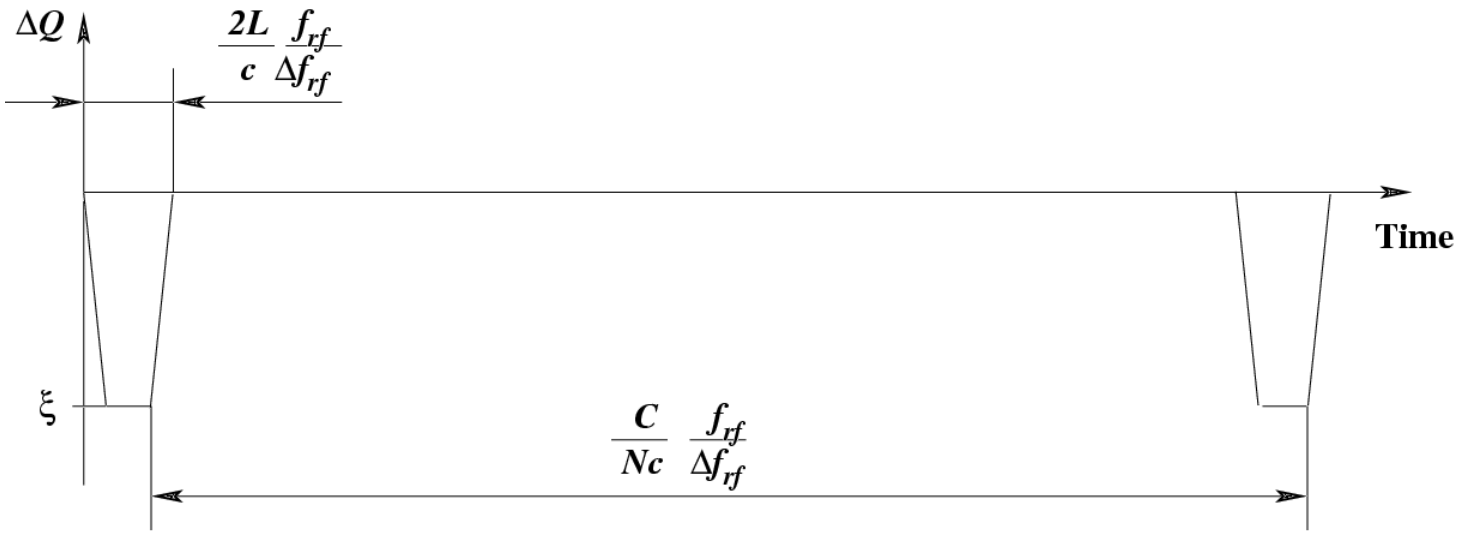
## 0.45 mrad full crossing angle




Tune change only near IP, smooth edges

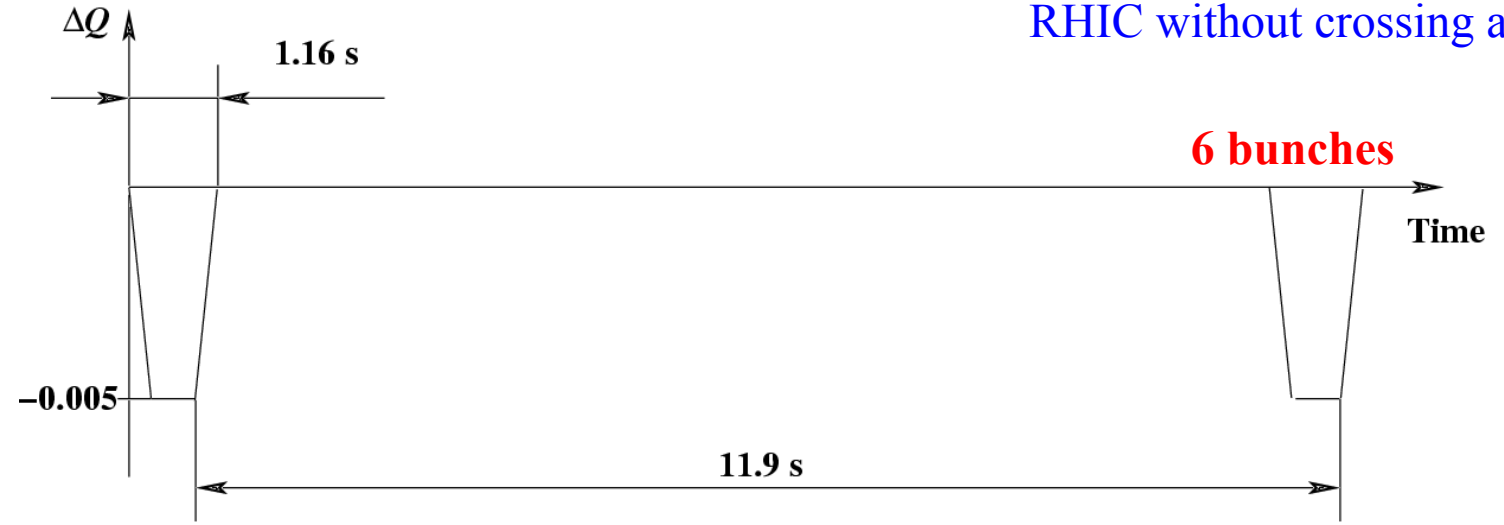

Wed Sep 26 2001
PLL Blue horizontal,
Au after 3h store
Cogged 3 buckets (fully separated longitudinally)
Cogged 2 buckets
Cogged 1 bucket
$\Delta Q_{meas}$=0.0007
$\rightarrow \varepsilon_N$=22μm
Beams colliding
Sign of crossing angles
(no tune change if all zero)
P. Cameron
0.2310
0.2309
0.2308
0.2307
0.2306
0.2305
0.2304
0.2303
0.2302
0.2301
0.2300
0.2299
0.2298
0.2297
0.2296
0.2295
11:04:15
11:04:25
11:04:35
11:04:45
11:04:55
11:05:05

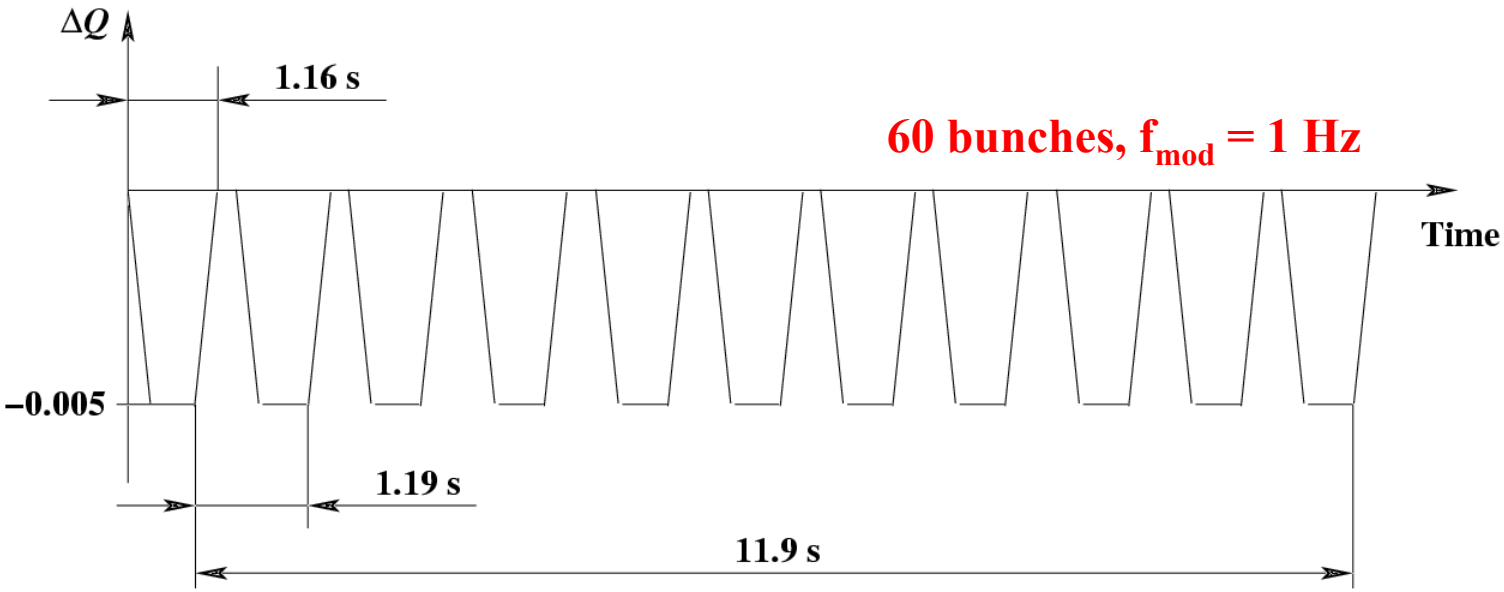
## Tune modulation frequency is determined by the fill pattern and $\Delta f_{rf}$



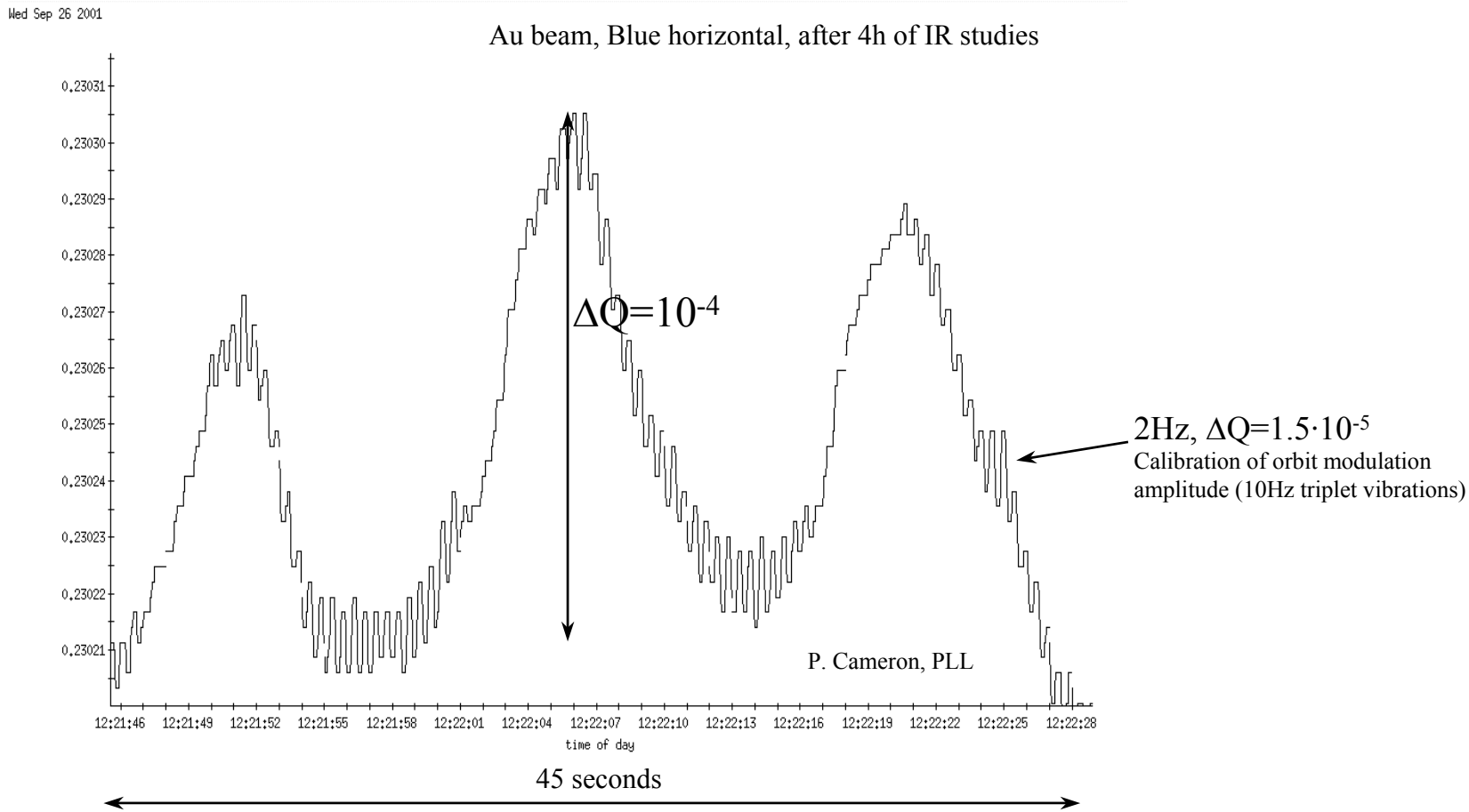

| | |
|---|---|
| $Q$ | tune |
| $\xi$ | beam-beam parameter |
| $C$ | machine circumference |
| $L$ | distance between crotches |
| $c$ | beam velocity (≈ speed of light) |
| $f_{rf}$ | radio frequency |
| $\Delta f_{rf}$ | difference between two rings |
| $N$ | number of bunches (symmetrically distributed) |

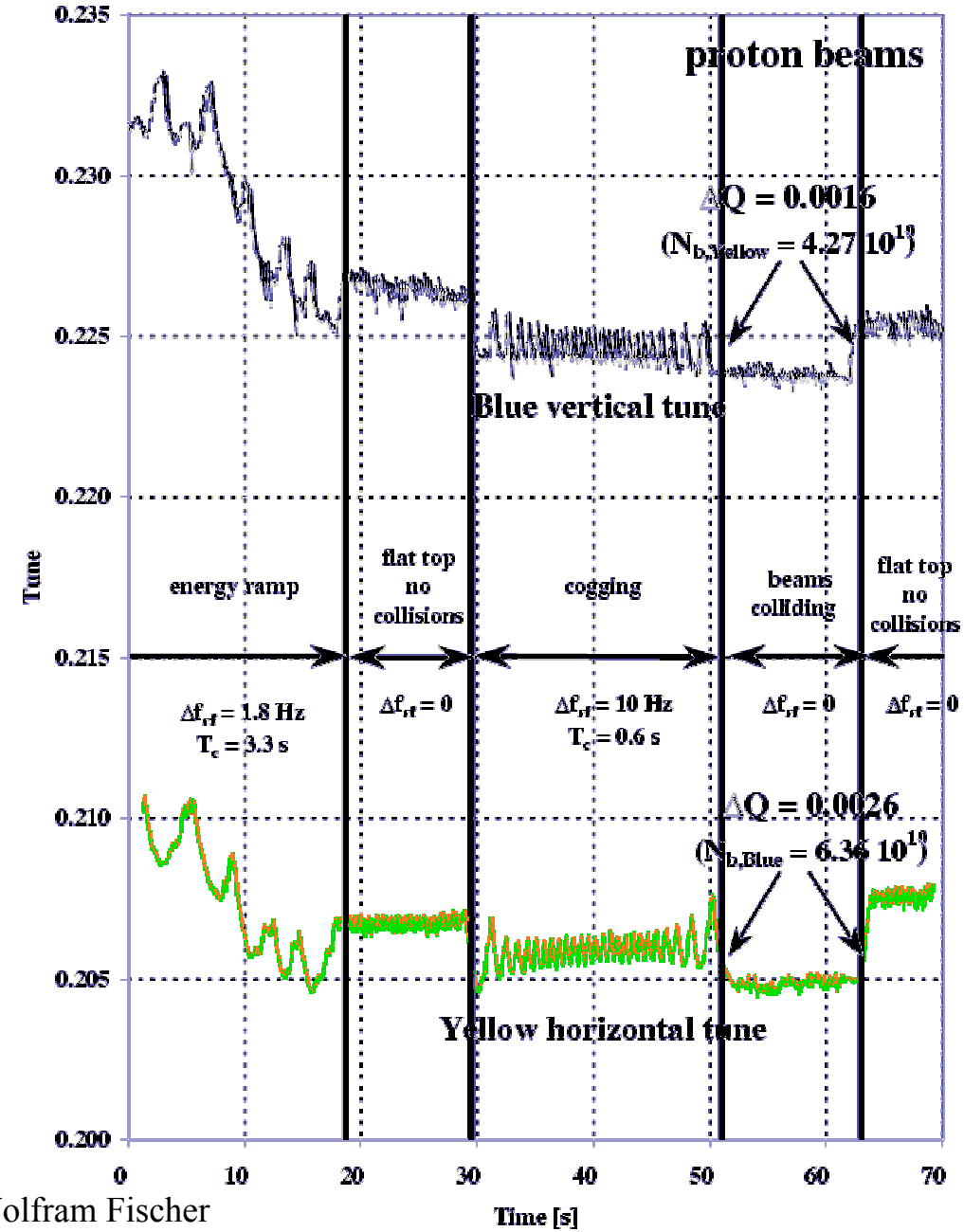
RHIC without crossing angle, $\Delta f_{rf} = 5$ Hz



## Unlocked rf frequencies at store (ramp-like tune modulation)






Follow tunes through ramp and flattop manipulations

- effect of unequal rf on ramp (tune modulation)
- synchronization and cogging at flattop

Measurement helped to understand and mitigate beam loss effects at beginning of store (effects can in extreme cases lead to lost stores)

PLL P. Cameron

- Unequal radio frequencies lead to modulated beam-beam interaction
- Can affect the tunes (head-on collisions) and emittances (long-range collisions)
- Tune modulation wave form and frequency depend on crossing angle, fill pattern and $\Delta f_{rf}$
- Effects may lead to unacceptable beam loss in operation
- Detrimental effects can be mitigated by
  - Larger transverse separation
  - Frequency locking (and possibly longitudinal separation)